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Radiocarbon in otoliths of yelloweye rockfish *(Sebastes ruberrimus)*: a reference time series for the coastal waters of southeast Alaska.

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Abstract

Atmospheric testing of thermonuclear devices during the 1950s and 1960s created a global radiocarbon (^{14}C) signal in the environment that has provided a useful tracer and chronological marker in oceanic systems and organisms. The bomb-generated ^{14}C signal retained in fish otoliths can be used as a permanent, time-specific recorder of the ^{14}C present in ambient seawater, making it a useful tool in age validation of fishes. The goal of this study was to determine ^{14}C levels in otoliths of the age-validated yelloweye rockfish (*Sebastes ruberrimus*) to establish a reference time series for the coastal waters of southeast Alaska. Radiocarbon values from the first year's growth of 43 yelloweye rockfish otoliths were plotted against estimated birth year to produce a ^{14}C time series for these waters spanning 1940 to 1990. The time series shows the initial rise of bomb ^{14}C occurred in 1958 in coastal southeast Alaskan waters and ^{14}C levels rose relatively rapidly to peak $\Delta^{14}C$ values (60–70‰) between 1966 and 1971, with a subsequent declining trend through the end of the record in 1990 (–3.2‰). In addition, the radiocarbon data, independent of the radiometric study, confirms the longevity of the yelloweye rockfish up to a minimum of 44 years and strongly supports higher age estimates. The yelloweye rockfish record provides a ^{14}C chronology that will be useful for the interpretation of ^{14}C accreted in biological samples from these waters and in future rockfish age validation studies.

Keywords: radiocarbon, otolith, rockfish, *Sebastes ruberrimus*, chronometer

Introduction

Atmospheric testing of thermonuclear devices in the 1950s and 1960s created a ^{14}C signal that can be traced in atmospheric, terrestrial, and marine environments (Nydal and Loveseth 1983; Kalish 1995). The introduction of ^{14}C into ocean surface waters provided scientists with information on carbon dioxide (CO_2) flux between the atmosphere and ocean, movement of water masses, and penetration rate of carbon to the deep sea (Rafter and Fergusson 1957; Broeker and Peng 1982; Kalish 1995). Temporal changes in ^{14}C have been documented in numerous ways and have had broad applications in studying processes in the fields of oceanography, climatology, geochemistry, and marine biology.

Changes of ^{14}C levels in seawater through time have been monitored directly and by proxy. Direct measurements of ^{14}C in seawater, such as those conducted in the Pacific Ocean under the Geochemical Ocean Sections Survey (GEOSECS; 1973–1974) and the World Ocean Circulation Experiment (WOCE; 1991–1993), provided one-time snapshots of oceanic ^{14}C on a global scale (Ostlund and Stuiver 1980; Key et al. 1996). These surveys, however, were not continuous and temporal changes in ^{14}C prior to the time of GEOSECS for specific ocean regions are largely unknown.

Hermatypic corals have been found to be accurate and useful recorders of past ^{14}C concentrations in ambient seawater because of their well-established annual banding patterns and the incorporation of dissolved inorganic carbon (DIC) from seawater into their skeletal structure during growth.(Nozaki et al. 1978; Druffel 1980). However, these warm-water reef-building corals are found only in equatorial and low latitude waters, and are not available for establishing ^{14}C records in high latitudes (Druffel 1987; Toggweiler et al. 1991; Weidman and Jones 1993).

In the past, the lack of suitable proxies for ^{14}C concentrations in seawater at high latitudes had limited the application of the time-specific bomb ^{14}C signal in such locations.

Kalish (1993) first recognized the utility of fish otoliths as a possible recorder of the concentration of ^{14}C in seawater. Otoliths are composed of a crystalline form of calcium carbonate known as aragonite (Degens et al. 1969). Otolith carbon is primarily derived (70–90%) from seawater DIC; the remainder (10–30%) from food, making the carbon isotope composition of otoliths similar to surrounding seawater (Farrell and Campana 1996; Kalish 1991; Schwarcz et al. 1998). The metabolic and temporal stability of otolith aragonite makes for a permanent record of assimilated ^{14}C (Kalish 1993; 1995). The composition and structure of the otolith, coupled with the well-established technique to age otoliths by examining annual banding, makes this structure a feasible proxy for tracking temporal changes of ^{14}C in seawater.

To establish a ^{14}C chronology with otoliths, known-age fish are necessary. The most reliable method utilizes juvenile fish (~ age-1) collected over a time period that extends back to the pre-bomb era; the use of juvenile fish allows the formation period of the otolith to be well constrained (Campana 1997). Alternatively, when juveniles are not available, ^{14}C chronologies can be established using otoliths from fish for which age estimates have been validated (Kalish et al. 2001). In this case, the assumption would be that the age is correct and the core material (the portion of the otolith formed when a juvenile) contains ^{14}C levels representative of the waters in which the fish spent its birth year. Because deepwater mixing rates and the penetration of the bomb ^{14}C signal are usually not known for particular regions of interest, this technique is most reliable for fishes that inhabit the mixed layer of the ocean, at least during the juvenile portion of their life history (Kalish 1995). Development of useful otolith-based ^{14}C chronologies requires otoliths from fish with birth dates that include the mid-1950s to early 1970s. This makes the technique well suited for long-lived species or those for which there is an archived otolith collection that spans this period (Kalish 1995).

In addition to discovering a new proxy for ^{14}C concentration in seawater, Kalish (1995) provided fisheries biologists with an important method of validating otolith-based age estimates of fishes. The discrete temporal variation of ^{14}C recorded in otoliths, when related to an appropriate reference ^{14}C time series, provides a basis for ^{14}C derived age estimates (Kalish 1995). To date, at least eight studies have effectively validated age estimates of fishes using this technique, many relying on established coral ^{14}C records in close proximity for temporal calibration (Kalish 1993; Kalish et al. 1996; Baker and Wilson 2001). These studies confirmed that the bomb ^{14}C signal was retained in fish otoliths, and validated the reliability of otoliths as sources of reference ^{14}C time series (Campana 1997).

The yelloweye rockfish (*Sebastes ruberrimus*) is a long-lived rockfish and a major component of the demersal longline and trawl fishery in the northeast Pacific Ocean (O'Connell and Carlile 1993; Yamanaka and Kronlund 1997; Fritz et al. 1998). This fish is found from the Aleutian Islands, Alaska to northern Baja California, Mexico, and inhabits the near-shore surface waters as a juvenile, moving to greater depths as an adult (Love et al. 1991). Based on growth zone counts in otoliths this species has an estimated longevity of more than 110 years, reaching a maximum of 118 years (O'Connell and Funk 1986; Munk 2001). Independent age estimates derived from the radiometric age validation technique confirmed that this species grows slowly, has a longevity that exceeds 100 years, and deposits annual growth zones that are easily quantified (Andrews et al. 2002). Prior age validation of the yelloweye rockfish makes it an ideal candidate for establishing a reference ^{14}C time series. The goal of this study was to determine the ^{14}C levels in otoliths from yelloweye rockfish to establish a time series for the waters and resident biota of coastal southeast Alaska.

Materials and Methods

Yelloweye rockfish were collected from the coastal waters off southeast Alaska by the Alaska Department of Fish and Game (ADFG), Juneau, AK in 2000. Samples came from either ADFG research survey operations or were randomly sub-sampled by ADFG from commercial fishing vessels returning to port. Sagittal otoliths were removed, cleaned, and stored dry in paper envelopes. Age was determined using one otolith from each pair via the break-and-burn technique by researchers at the Mark, Tag, and Age Laboratory, ADFG. This technique entails breaking the otolith in the transverse plane and burning the broken end carefully over a flame, enhancing the contrast between translucent and opaque growth zones (Williams and Bedford 1974; Chilton and Beamish 1982). Date of capture, final estimated age, assigned year class, readability code, and reader identification information were provided for each sample. The other otolith of the pair was left intact for radiocarbon analysis.

Forty-three yelloweye rockfish otoliths, with estimated birth years ranging from 1940 to 1990 (age range 10–60 years) and with the highest age estimate confidence by ADFG, were chosen for ^{14}C analysis. Ten birth years (pre- to post-bomb) were replicated, with 2–3 otoliths analyzed for each year, to assess the reproducibility of results using the methodology of this study. Radiocarbon levels were determined for the core of the otolith, which constituted the first year of growth for the specimen, when it inhabited surface waters. To determine the average length and width, and minimum depth of the core, whole and broken-and-burnt otoliths from adult yelloweye rockfish were examined under a Leica® dissecting microscope with attached Spot RT® video camera and measured using Image Pro Plus® image analysis software. In preparation for coring, whole otoliths were mounted on PVC discs with fiberglass resin, distal side up. Cores were extracted using a milling machine with a titanium coated end mill (2.4 mm diameter). To minimize the extraction of material deposited after the first year of growth, length, width, and depth parameters of the otolith core were used to guide coring. Because the first year of growth in yelloweye rockfish otoliths is clearly visible from the otolith surface, we were able to visually correct for individual variability in otolith core size. Coring produced a powdered sample; the weight of this material was measured to the nearest 0.1 mg. Sample weights averaged 5.6 ± 1.3 mg.

In preparation for ^{14}C analysis, otolith aragonite ($CaCO_3$) was converted to pure carbon, in the form of graphite (Vogel et al. 1984; 1987). The ^{14}C in the produced graphite was measured by accelerator mass spectrometry (AMS) at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. Radiocarbon values are reported as $\Delta^{14}C$, the per mil fractional difference of the sample ^{14}C:^{12}C atom ratio from that of the international accepted ^{14}C dating reference (Stuiver and Polach 1977). An assumed $\delta^{13}C$ value of 0 ± 3‰ was used in calculating the $\Delta^{14}C$ values. This $\delta^{13}C$ value is representative of expected $\delta^{13}C$ marine carbonate values (Stuiver and Polach 1977).

The ^{14}C values were placed in the time series based on their assigned birth years. Andrews et al. (2002) determined a coefficient of variation of 4% for age estimated from growth zone counts. Chi-squared based analysis of the agreement between the lead-radium data and the expected radiometric ingrowth curve indicated that the actual age of a sample is constrained within ± 10% of the growth-zone-based age estimates. This supports the assumption that the growth zones formed and quantified in yelloweye rockfish otoliths are annual and that the age estimation procedures are valid. On the basis of these results we have 90% confidence in assigned birth years; hence, the use of core material as a temporal proxy for radiocarbon is valid and any potential variation in the calculated birth date of each radiocarbon sample can be attributed to reader variability (coefficient of variation (CV) = 4%, rounded to the nearest whole number (Chang 1982)).

The year of initial bomb ^{14}C rise in the yelloweye rockfish record was determined through an error-weighted fit of an exponential function to the initial rise section of the record. An average pre-bomb (1940–1956) radiocarbon value was determined; the exponential function was fit to the initial bomb ^{14}C rise values (1940–1966), and the year in which the fitted exponential rose to the + 2 standard deviation (SD) level of the pre-bomb average was calculated. The year of initial rise in ^{14}C was also determined as the year in which the first sample ^{14}C value was significantly higher (+ 2 SD criteria) than the mean pre-bomb level. The yelloweye rockfish radiocarbon record was compared to Pacific Ocean hermatypic coral records (Guilderson et al. 1998; Toggweiler et al. 1991; Druffel et al. 2001), northern hemisphere atmospheric radiocarbon records (Levin et al. 1994; McCallum and Wittenberg 1962), and two otolith-based records (Campana 1997; Kalish et al. 2001) to assess the correlation of temporal ^{14}C changes.

Results

Radiocarbon values measured for the forty-three otolith cores from yelloweye rockfish showed considerable temporal variation (Table 1). A comparison of replicated samples for ten birth years indicated the largest differences in ^{14}C values within a birth year occurred during the period of rapid increase (replicate samples from 1960-1967), and replicated measurements for birth years during pre- and post-bomb showed very little difference, except in 1975 samples (Table 1). Given the rapid rise in ^{14}C values between 1960 and 1968 (~ –60‰ to ~ +60‰), the differences between replicates during this period are within expectations due to the ± 1–2 year uncertainties in the estimated birth years for the otolith samples.

When ^{14}C values were plotted against estimated birth year, the values produced a ^{14}C time series for coastal southeast Alaskan waters from 1940 to 1990 (Fig. 1). The time series revealed the characteristic bomb ^{14}C rise, and subsequent decline, over this time period. Pre-bomb (1940–1956) ^{14}C values measured in yelloweye rockfish otoliths showed more scatter than expected from ^{14}C uncertainties but showed no trend over time, averaging –102.2 ± 9.3‰ (mean ± SD). The first evidence of a ^{14}C increase due to atmospheric testing of thermonuclear devices was the abruptly higher ^{14}C value obtained for the 1958 sample. This first indication of the start of the bomb ^{14}C rise was in agreement with the exponential fit analysis of the ^{14}C time series; the fit exponential intercepted the +2 SD pre-bomb level in 1958. In addition, the 1958 sample was the first to have a ^{14}C value that was significantly above pre-bomb radiocarbon levels using a + 2 SD criteria (± 18.5‰). The rise in ^{14}C continued until reaching a maximum in 1966 with a ^{14}C value of 68.9‰ and ^{14}C levels remained high in a plateau that extended through 1971, followed by a decreasing trend until 1990 (last year of sampling).

A qualitative comparison of the yelloweye rockfish ^{14}C record with existing records revealed similarities and differences in the temporal pattern. A hermatypic coral from Nauru Island in the western tropical Pacific (Guilderson et al. 1998) had a similar initial rise time (~ 1959), but a more gradual rate of rise and a later peak in ^{14}C values, in the early 1980's, compared to the yelloweye rockfish record (Fig. 2). Radiocarbon values in annual bands of corals from the Hawaiian Islands (Oahu, Toggweiler et al. 1991; Hawaii, Druffel et al. 2001) were more similar temporally to the yelloweye rockfish record, increasing from the late 1950s and peaking in 1971. The northern hemisphere atmospheric ^{14}C record (Levin et al. 1994;

McCallum and Wittenberg 1962) had a more abrupt rise, an earlier peak time (mid 1963), and a much higher amplitude, with a total rise of 1000‰, than the yelloweye rockfish record (Fig. 3).

Discussion

This study establishes the first ^{14}C time series for the coastal waters of southeastern Alaska by taking advantage of the existing radiometric age validation of the yelloweye rockfish (Andrews et al. 2002). The time-series developed using the growth-zone based ages to predict birth years and ^{14}C measurements on the otolith cores shows the basic expected pattern of variations due to the atmospheric testing of thermonuclear devices.

Comparison of a northern hemisphere atmospheric ^{14}C record with the yelloweye rockfish and Pacific Ocean coral time series shows the expected slower rise and relatively modest peak values of the oceanic records due to air-sea CO_2 exchange and isotopic equilibration effects on the movement of the atmospheric ^{14}C pulse into the surface ocean waters. The significant differences between the two coral records (Nauru Island and Hawaiian Islands) reflect the influences of regional oceanographic factors, such as mixed layer thickness, vertical convective and diffusive mixing, deep water upwelling, and subsurface horizontal advection (Druffel 1987; Mahadevan 2001). The lower pre-bomb ^{14}C levels and decreased amplitude of the bomb ^{14}C pulse in the yelloweye rockfish record suggests the influence of upwelled ^{14}C-depleted waters on the southeast Alaskan coastal surface waters. The similarity in peak timing and overall shape between the yelloweye rockfish and Hawaiian Islands coral records also suggests a similarity in the effective mixed layer depth in the two regions.

The utilization of the yelloweye rockfish record as a reference ^{14}C time series for coastal southeast Alaskan waters rests, in part, on an adequate accounting of the potential sources of uncertainty in the data set. Potential sources of inaccuracy in the yelloweye rockfish ^{14}C data, beyond the analytical uncertainty in the AMS ^{14}C measurements, include otolith coring inaccuracies and growth-zone age estimation uncertainties. Incorporation of more recently formed otolith material (age 2 or 3 years) in the sample could introduce a slight shift, although essentially negligible, in the ^{14}C value depending on the time of otolith formation in relation to the ^{14}C signal. For example, the introduction of 5% of the sample mass with a ^{14}C content that differs by 100‰ from the year-1 material would shift the measured ^{14}C content by only 5‰. While it is possible that incorporation of more recently formed material may have inadvertently occurred, the sampling methodology was specifically designed to limit the possible inclusion of non year-1 material.

The uncertainty associated with yelloweye rockfish age estimates, and consequently birth year, have two potential sources, 1) contribution of error from growth zone counts or 2) error associated with the radiometric age validation. The potential for inaccuracy based on radiometric age determination was assessed and the possible error in ageing constrained to ± 10% by the agreement between the Pb-Ra data and the expected ingrowth curve (Andrews et al. 2002). This result provides high confidence (90%) in the assignment of ages from growth zone counts and supports the conclusion that the growth zones formed in yelloweye rockfish otoliths are annual. Henceforth, we infer that the growth zones are accurate indicators of age and that the potential error associated with birth date determination can be attributed to the growth zone counts (CV = 4%). In addition, the otoliths used in this study were chosen specifically for the ease of otolith read and highest rank in age estimate confidence, making them best-case examples of precise age determinations.

A possible source of within year variation of ^{14}C values is related to the geographic location of individual fish in relation to variable oceanographic conditions. Individual juvenile yelloweye rockfish occupy relatively limited regions during their first year of growth and factors such as local bathymetry, coastal upwelling, and freshwater input are likely to have an impact on water column structure and processes, and therefore the ^{14}C content of the local waters. The within year variability of otolith ^{14}C values from regional effects is evident in the pre-bomb section of the ^{14}C time series. The observed ± 9.3‰ (1-SD) scatter of the pre-bomb values is considerably larger than expected from the analytical uncertainties of the AMS ^{14}C measurements (~ ± 3–4‰).

These regional effects may also be responsible for the difference between the 1975 post-bomb replicates. Estimation of post-bomb ^{14}C variations is more difficult than for pre-bomb levels because of the general declining trend of post-bomb ^{14}C values. By fitting the post-bomb ^{14}C data (1966-1990) with a linear regression an estimate of variability was obtained from the residuals. The estimate of variability in post-bomb otolith ^{14}C values from regional effects (± 12‰; 1-SD) is 30% larger than the estimate for the pre-bomb portion of the time series. Larger variability in the post-bomb compared to the pre-bomb samples may be attributed to the larger contrast between the ^{14}C contents of the upwelled depleted waters (which have not yet been effected by bomb ^{14}C input) and the atmosphere (which in 1975 was still ~ 400‰ above the pre-bomb atmospheric values). Such variability is evident in ^{14}C fluctuations associated with ENSO-related upwelling of the coral-based record for the surface waters in the Galapagos (Guilderson and Schrag 1998).

The influence of short-term regional-scale changes in oceanographic conditions, such as ENSO events, may also be a source of ^{14}C variation in the yelloweye rockfish record. The lack of a ^{14}C time series and long-term records of oceanographic conditions in the coastal southeast Alaskan waters, however, makes it difficult to estimate the impact of such changes. Despite this lack of information, the variability in the pre- and post-bomb sections of the yelloweye ^{14}C time series puts limits on the reproducibility of ^{14}C values obtained from the otoliths (± 9‰ for the pre-bomb and ± 12‰ for the post-bomb).

Comparison of the yelloweye rockfish ^{14}C record to two otolith-based northern hemisphere ^{14}C chronologies (Fig. 4), the northwest Atlantic haddock (Campana 1997) and Barents Sea arcto-Norwegian cod (Kalish et al. 2001), shows nearly identical years of initial rise and rates of ^{14}C rise, and very similar overall ^{14}C pulse shapes. The lower pre-bomb levels of the yelloweye rockfish record suggests a more significant influence of ^{14}C-depleted upwelled waters in coastal southeast Alaskan waters, while the relatively constant post-bomb values of the arcto-Norwegian cod record suggests the possible influence of subsurface advection (Kalish et al. 2001). However, the generally similar ^{14}C time series obtained for these three otolith-based studies suggests that the oceanographic conditions relevant to the temporal evolution of ^{14}C concentrations in the waters inhabited by these fishes were similar.

The initial rise in bomb ^{14}C occurs in essentially the same year (1958) in the yelloweye rockfish record and the two otolith-based records. In addition, the two Pacific coral records show the first indication of rising ^{14}C levels between 1957 and 1960. While the considerable differences between these records following the initial rise reflects oceanographic influences on the uptake and redistribution of bomb ^{14}C, the relative synchrony of the initial rise is expected as it reflects the transfer of bomb $^{14}CO_2$ into the upper layers of the global ocean. The synchrony of the initial bomb ^{14}C rise is of particular relevance to validation of otolith-based age estimates of fishes. For example, if the intent of this study were to validate the otolith-based age estimates for the yelloweye rockfish (rather than establish a reference ^{14}C time series), it would have been sufficient to measure the ^{14}C content of relatively few otoliths thought to span the initial rise in

^{14}C (eg. ~ 1950 to ~ 1965) and compare this to the known time of initial rise. From this perspective, and independent of the radiometric validation of the otolith-based age estimates (Andrews et al 2002), the initial ^{14}C rise in the yelloweye rockfish time series (1958) is in agreement with the initial rise in the global surface ocean (1957-1960); validating growth-zone counts up to a minimum of 44 years. This confirmation of age to within ~ ± 2 years for 44 year old samples provides strong support for the accuracy of the growth-zone based age estimates and an estimated longevity >100 years ages. Reducing the effort of ^{14}C based age validations to a small number of samples centered on the years encompassing the initial bomb ^{14}C rise would reduce the need for extensive reference ^{14}C time series and increase the financial viability of ^{14}C age validation studies.

Radiocarbon measured in yelloweye rockfish otoliths has established the first high latitude pre- to post-bomb ^{14}C time series in the northeast Pacific Ocean. The ^{14}C record from yelloweye rockfish otoliths reflects the characteristic rise in radiocarbon due to the anthropogenic introduction of radiocarbon during the 1950s and 1960s, and is similar to records created from other fish otoliths throughout the world's oceans. This study is the first to apply the bomb ^{14}C validation technique to the rockfish family (Scorpaenidae) and the presence of the distinct bomb ^{14}C signal in yelloweye rockfish otoliths demonstrates the potential value of this ageing technique for other rockfish species. The reference ^{14}C time series of coastal southeast Alaskan waters produced in this study will have particular usefulness validating age estimates of other long-lived rockfishes with otoliths that are difficult to age (Cailliet et al. 2001) and will provide a basis for future age and growth studies of other commercially important fishes and organisms in this region. The published success of the ^{14}C technique on other fishes, the conservative structure and composition of otoliths, and the high longevity of many fish species, allows for the use of otoliths as a reliable recorder of ^{14}C concentration in seawater. Because fish can be collected at most latitudes and depths in the ocean, fish otoliths should be further explored as a recorder of past ^{14}C concentrations in seawater

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Table I. Summary of fish and otolith data from yelloweye rockfish collected off the coast of southeast Alaska. Resolved age is the final age estimate given by Alaska Department of Fish and Game. Birth year is sample year (2000) minus the resolved age. Age error is the uncertainty associated with the age estimate (coefficient of variation = 4%; rounded to the nearest whole number). Radiocarbon values in the otolith cores of yelloweye rockfish are expressed as $\Delta^{14}C$. Radiocarbon values for replicated birth years were from otoliths of individual fish.

Resolved age	Birth year	Age error (± year)	$\Delta^{14}C$ (‰)		
60	1940	2	-107.6 ± 2.8		
58	1942	2	-112.5 ± 2.7		
56	1944	2	-106.1 ± 2.8		
54	1946	2	-85.6 ± 2.8		
52	1948	2	-96.1 ± 2.6		
50	1950	2	-109.4 ± 3.5	-110.6 ± 2.7	
48	1952	2	-92.4 ± 3.4		
44	1956	2	-99.8 ± 3.6		
42	1958	2	-65.4 ± 2.4		
40	1960	2	-54.9 ± 2.8	-72.4 ± 3.5	
39	1961	2	-94.7 ± 2.7		
38	1962	2	-50.7 ± 3.0	-37.6 ± 3.0	
37	1963	1	-75.1 ± 2.9		
36	1964	1	-22.0 ± 3.0	-43.4 ± 3.0	
35	1965	1	35.1 ± 3.9	-48.8 ± 3.3	-7.4 ± 3.1
34	1966	1	57.6 ± 3.7	68.9 ± 3.1	
33	1967	1	57.8 ± 4.1	39.6 ± 3.3	
32	1968	1	62.2 ± 2.6		

31	1969	1	49.1 ± 3.2		
30	1970	1	64.0 ± 4.0	60.9 ± 4.1	61.7 ± 3.4
29	1971	1	64.7 ± 3.3		
28	1972	1	43.1 ± 3.2		
26	1974	1	26.0 ± 3.1		
25	1975	1	40.8 ± 3.9	8.6 ± 3.8	
24	1976	1	39.9 ± 3.9		
22	1978	1	30.1 ± 3.3		
20	1980	1	26.8 ± 3.9	24.1 ± 3.3	
18	1982	1	-2.1 ± 3.0		
16	1984	1	33.4 ± 3.1		
14	1986	1	-3.4 ± 3.0		
10	1990	0	-3.2 ± 2.6		

Figure Captions

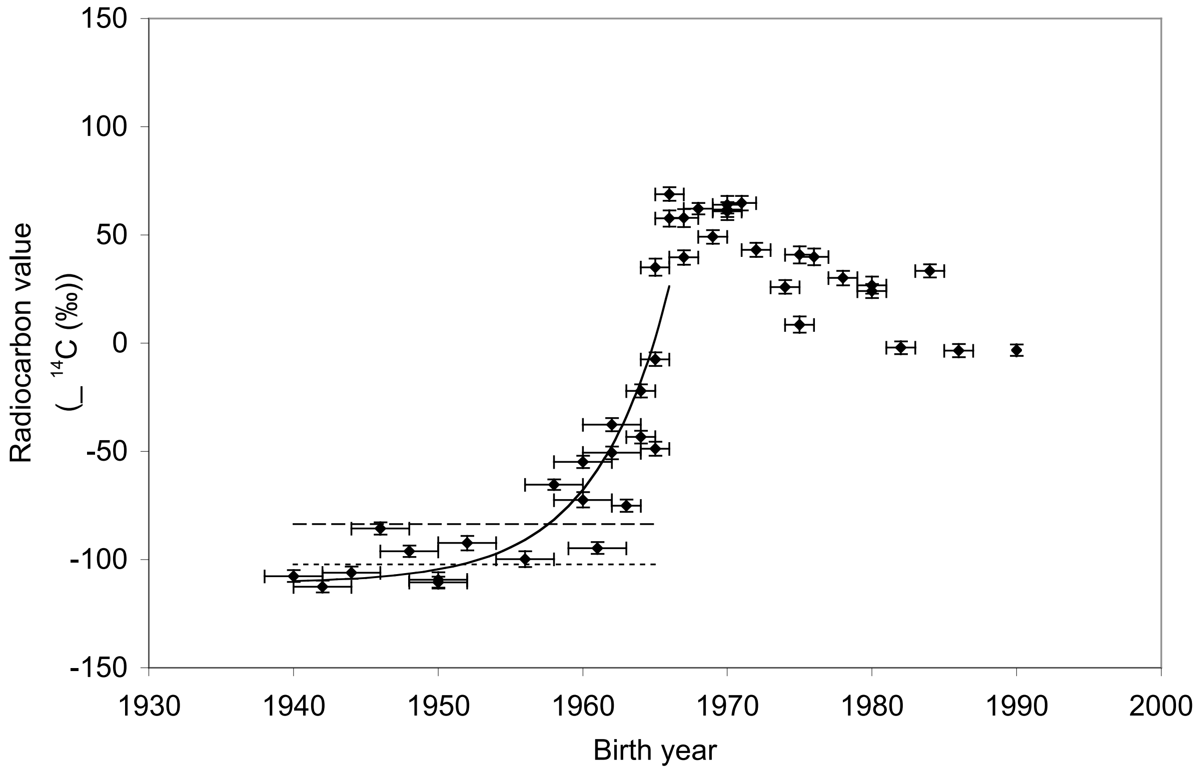
Figure 1. Radiocarbon ($\Delta^{14}C$) values in otolith cores for yelloweye rockfish (*Sebastes ruberrimus*) otoliths (n = 43) in relation to birth year (solid circles). Horizontal error bars represent the uncertainty associated with age determination from growth zones (CV = 4%, rounded to the nearest whole number). Vertical bars represent the 1-sigma AMS analytical uncertainty. The solid line shows the exponential line used in the exponential fit method to determine the year of initial rise from pre-bomb levels (the fit function had the form Y=A+B*exp(C*X) with Y: ^{14}C, X: Birth Year, and A, B and C: fit parameters). The dashed line represents the + 2 SD level (–83.6‰) associated with the average pre-bomb value (–102.2 ± 9.3‰; dotted line); the + 2 SD line was used in the exponential fit method and the year-of-initial-rise method.

Figure 2. Radiocarbon data ($\Delta^{14}C$) from yelloweye rockfish (*Sebastes ruberrimus*) otolith cores (solid circles) and hermatypic corals from the Nauru Islands in the western tropical Pacific (solid diamonds; Guilderson et al 1998) and Hawaiian Islands in the subtropical North Pacific (open triangles; Toggweiler et al. 1991; Druffel et al. 2001).

Figure 3. Radiocarbon data ($\Delta^{14}C$) from yelloweye rockfish (*Sebastes ruberrimus*) otolith cores (solid circles) and a northern hemisphere atmospheric radiocarbon record (dashed line; Levin et al. 1994; McCallum and Wittenberg 1962). Vertical axes are adjusted to show the correspondence of the rise and peak of radiocarbon values.

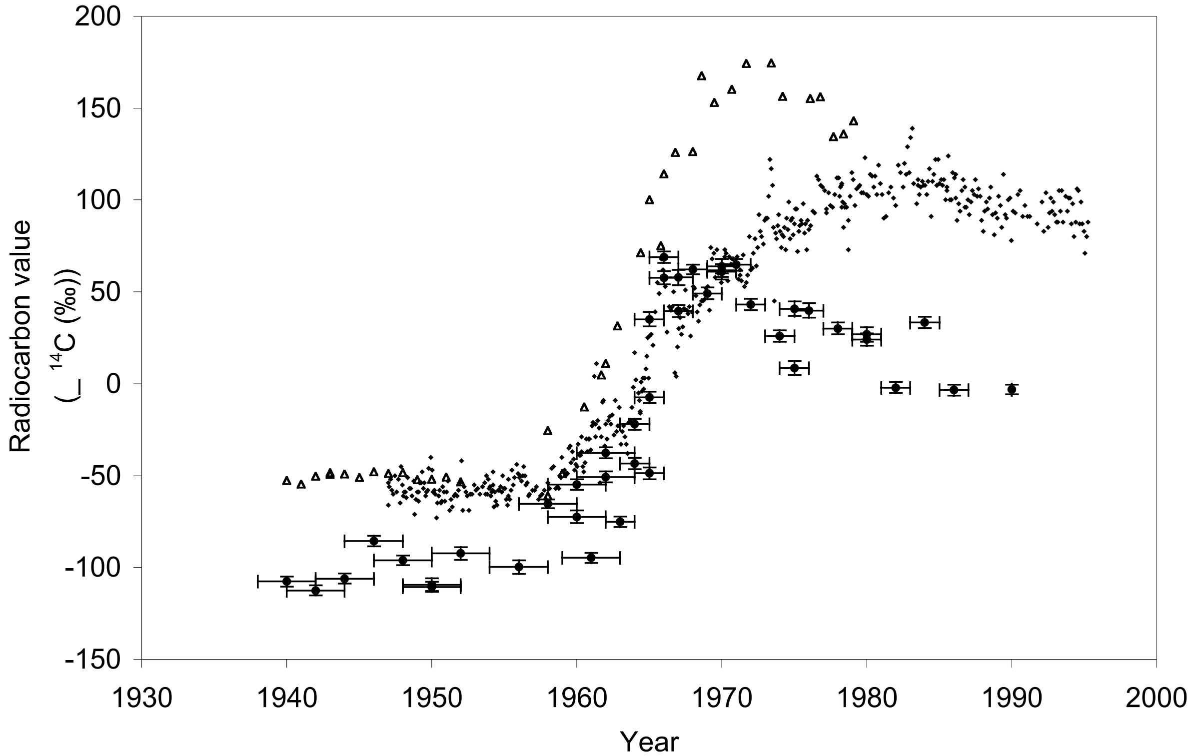
Figure 4. Radiocarbon data ($\Delta^{14}C$) from three fish species with birth years from 1919 to 1992. The birth dates for northwest Atlantic haddock, *Melanogrammus aeglefinus* (crosses; Campana 1997), Barents Sea arcto-Norwegian cod, *Gadus morhua* (open squares; Kalish et al. 2001), and yelloweye rockfish, *Sebastes ruberrimus* (solid circles), were determined from validated age estimates.

Figure 1.



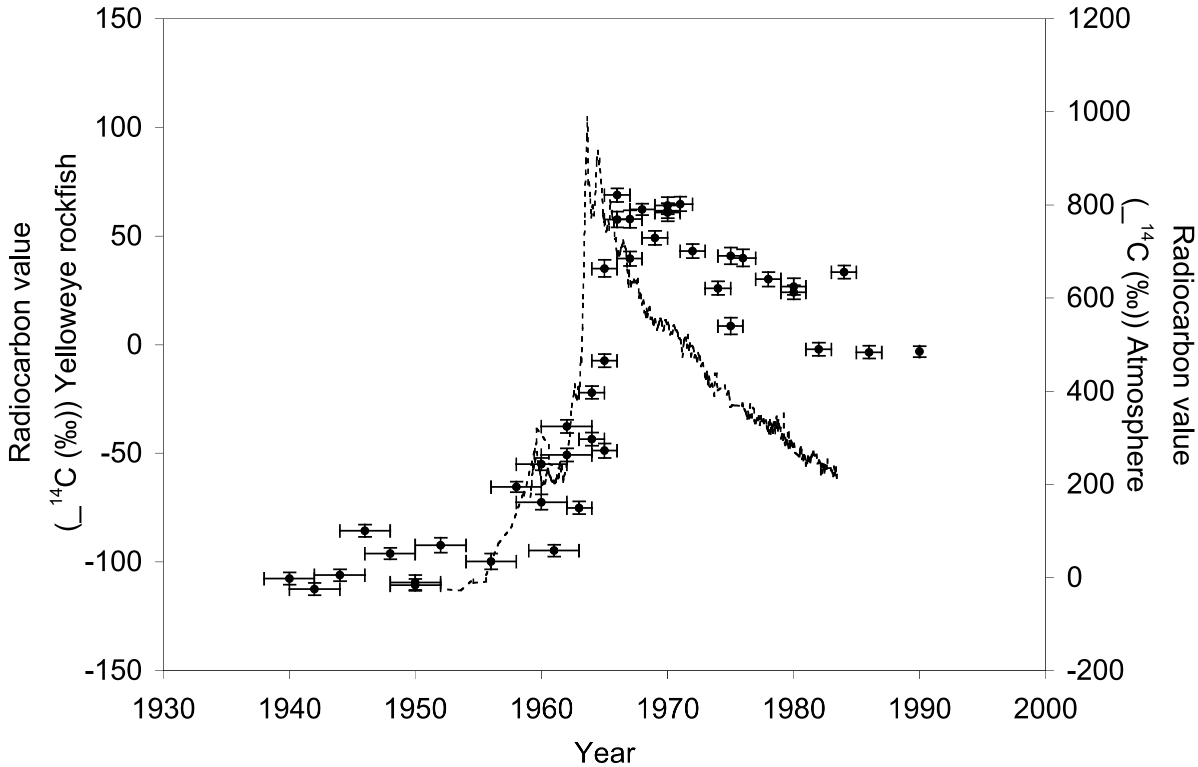
150
100
50
0
-50
-100
-150
Radiocarbon value
(_ 14C (‰))
1930
1940
1950
1960
1970
1980
1990
2000
Birth year

Figure 2.



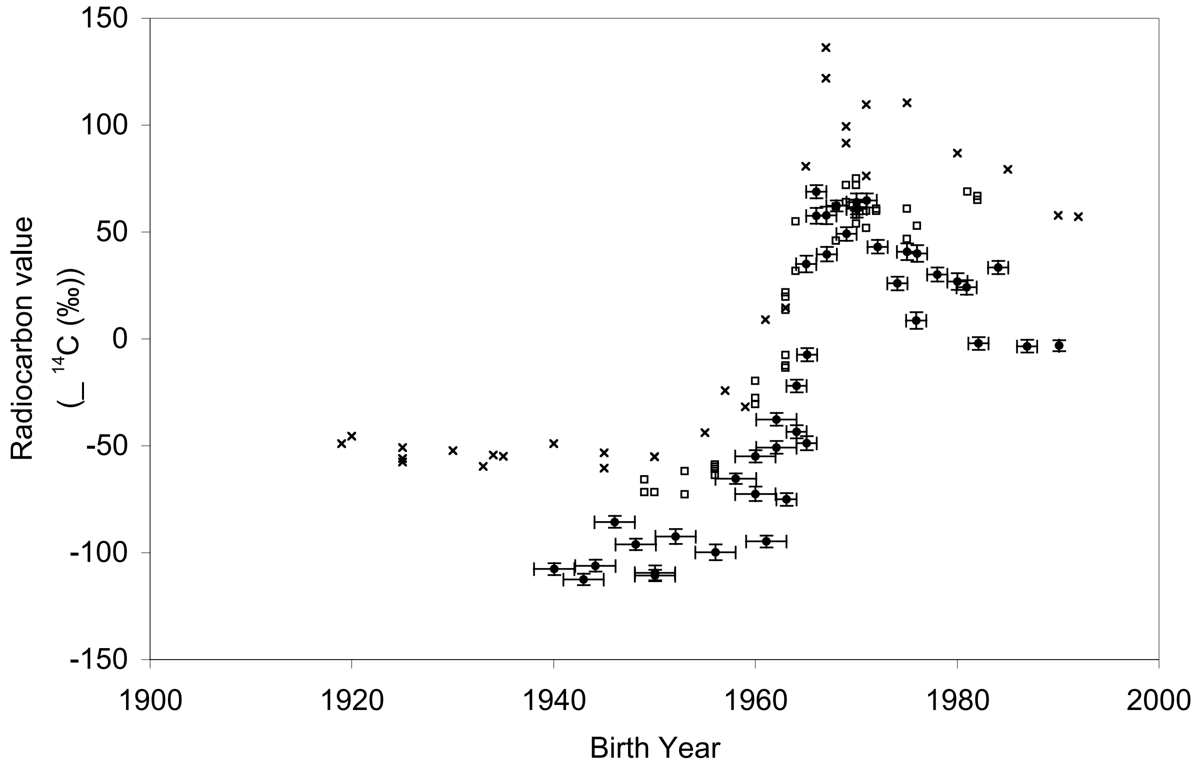
200
150
100
50
0
-50
-100
-150
1930
1940
1950
1960
1970
1980
1990
2000
Year
Radiocarbon value
(_ 14C (‰))

Figure 3.



150
100
50
0
-50
-100
-150
1200
1000
800
600
400
200
0
-200
1930
1940
1950
1960
1970
1980
1990
2000
Year
Radiocarbon value
(_14C (‰)) Yelloweye rockfish
Radiocarbon value
(_14C (‰)) Atmosphere

Figure 4.



150
100
50
0
-50
-100
-150
Radiocarbon value
(_ 14C (‰))
1900
1920
1940
1960
1980
2000
Birth Year